Solar Flares and Magnetospheric Particles: Investigations Based Upon the ONR-602 and ONR-604 Experiments

Performance Report

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"Solar Flares and Magnetospheric Particles: Investigations Based Upon the ONR-602 and ONR-604 Experiments"

I. Introduction:

This performance report covers work accomplished under ONR Grant N00014-90-J-1466 related to the radiation environment in near-Earth space. The goal of the research is to measure and describe, quantitatively, the Geospace radiation environment in which men and spacecraft must survive and function. The tools for this investigation are the data returned by the ONR-602 and ONR-604 experiments, both flown under the auspices of ONR and the Air Force Space Test Program, augmented by correlative databases of both space-based and ground-based data. The investigation involves data analysis, modeling and applications to a variety of space equipment and environments.

This report builds upon the detailed Technical Report (Fall, 1992) and the previous performance reports. For the current period, the principal effort was in the analysis of the solar energetic particle events that occurred during the CRRES mission, focusing upon the helium component. In addition, we have looked at the galactic quiet-time helium to help determine the modulation level during the CRRES Mission.

II. Solar Energetic Particle (SEP) Analysis:

In the previous report, we described the twelve flares that have been isolated from the ONR-604 data and discussed the measurement of the Helium energy spectrum. This included the background rejection procedures, flux calculations, proton spectra and comparison to other data. What remained was to complete the validation of the results and to look more carefully at the helium isotopes.

A. Comparison with other data:

For the helium spectra, we had available the 25-93 MeV/nucleon helium flux from the IMP-8 spacecraft. We have now obtained additional data (courtesy University of Chicago) for the 70-95 MeV/nucleon helium flux. Utilizing this, we have compared the flux calculated from ONR-604 (for $L > 6$) to that measured by IMP-8. The result is shown in Figure 1 for CRRES orbits 774 and 825 which differ by almost two orders of magnitude in the helium intensity. The agreement between IMP-8 and ONR-604 is very good.

Figure 2 shows another comparison. Here the full energy spectrum measured by ONR-604 for SEP event #7 (June 4, 1991) is compared to the two available IMP-8 points. Again the 70-95 MeV/nucleon interval is in good agreement, while the IMP-8 25-93 MeV/nucleon interval appears to be lower than expected from integrating the ONR-604 spectrum. Whether the discrepancy is due to a saturation in the IMP-8 rate at these high flux levels (most likely) or to a turn-over in the actual SEP Spectra (unlikely) has not yet been determined. The agreement of the 70 - 95 MeV/nucleon points at an intensity a factor of 10 lower suggest that the 25 - 93 MeV/nucleon interval is saturated.

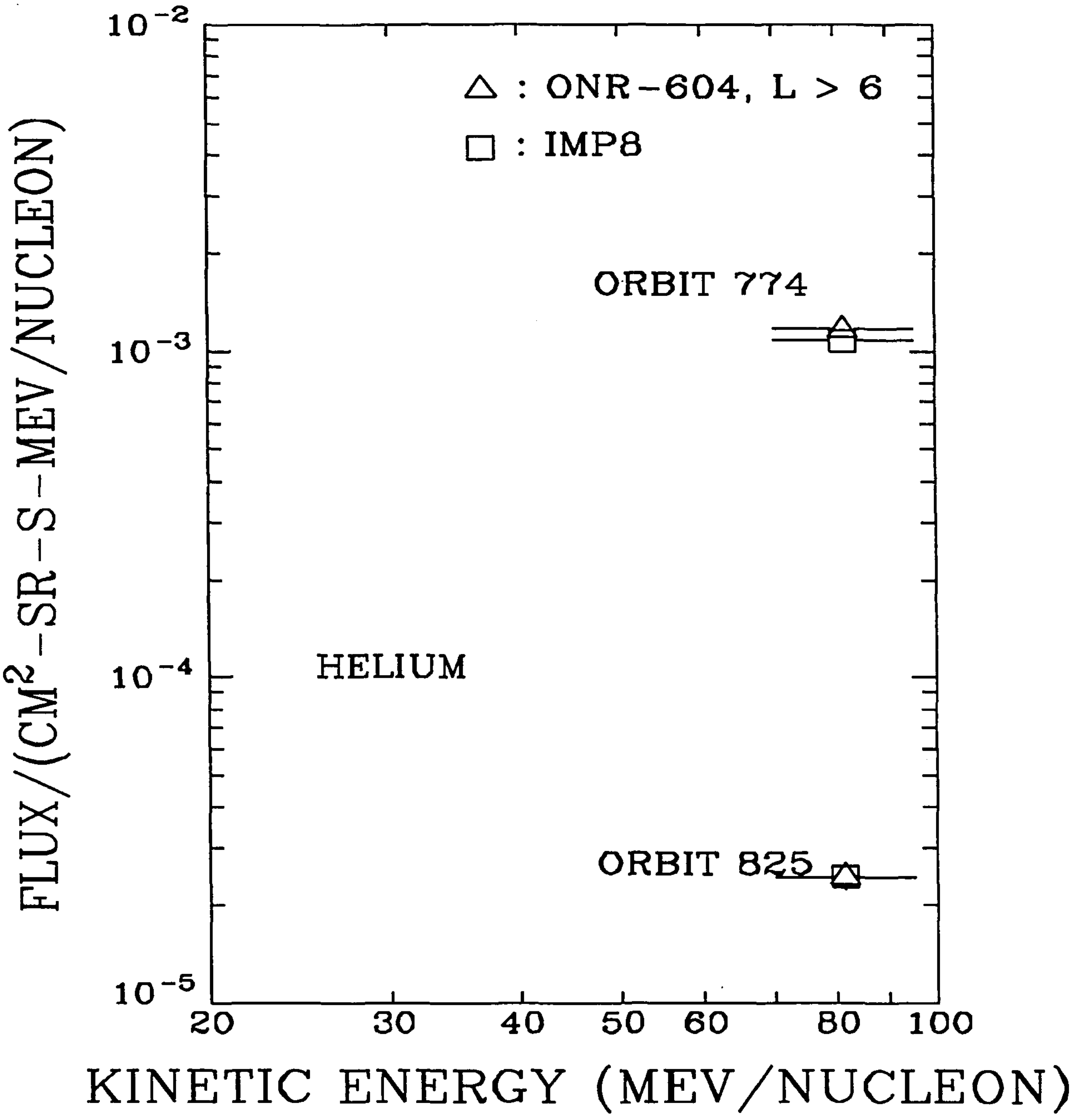


Figure 1. Comparison of the 70 - 95 MeV/nucleon Helium flux measured by IMP-8 and ONR-604 on CRRES for orbits 774 and 825.

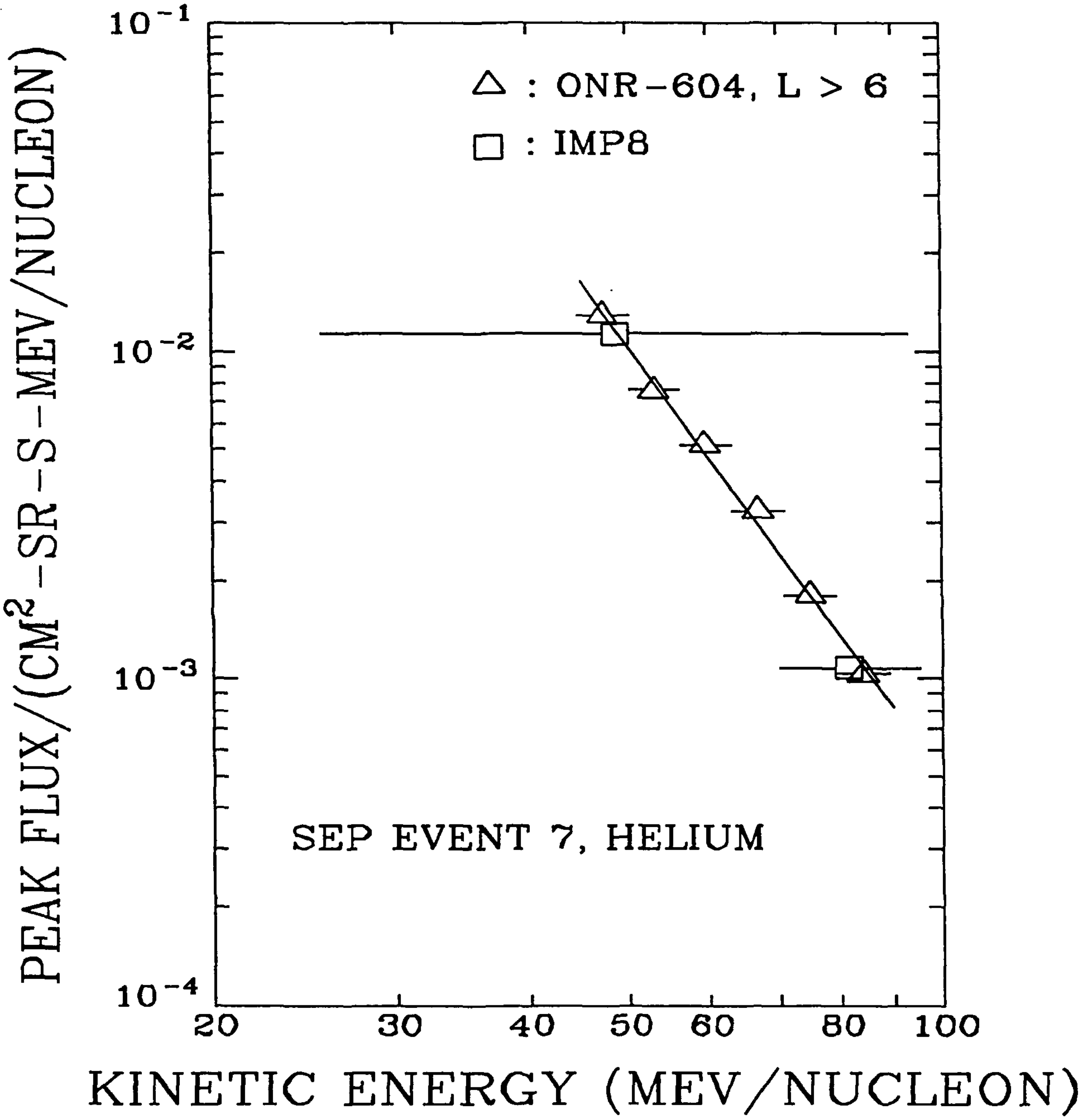


Figure 2. Comparison of IMP-8 data with the CRRES energy spectrum measured for helium on 4 June 1991.

The question of the flare proton spectra was raised in the previous report. We have been using the GOES proton channels since during a flare the ONR-604 P3 events (protons) are effectively eliminated by the instrument's priority system. We have now extended the previous analysis to include proton data from IMP-8 as well as GOES. A comparison for two flares SEP 1 (25 Jan. 1991) and SEP 7 (4 June 1993) are shown in Figure 3. The agreement is very reasonable, and used together, these two datasets can provide a good measure of the important proton energy spectrum for the different flares.

B. The Helium Isotopes

The ONR-604 instrument can separate the isotopes of Helium as noted in previous reports. One indication of a possible heavy ion enhancement in solar flares has been an accompanying enhancement in the ^{3}He/^{4}He ratio. The preliminary mass histograms for the helium from the different flares showed a "tail" on the low-mass side of the ^{4}He peak. This reduces the mass resolution, making it more difficult to determine a ^{3}He/^{4}He ratio.

We have investigated this effect in detail using the quiet-time Galactic Cosmic Ray (GCR) helium which is known to contain ~10% ^{3}He. We have discovered that part of the resolution degradation is due to detector edge effects. This is illustrated in Figure 4. The left plot shows the resolution of GCR helium isotopes for a cut $R < 20$ mm. This means the projected point of incidence on the stopping detector (as determined from the instrument's trajectory system) must be within a radius of 20 mm from the centerline of the telescope. Separate plots are shown for ID = 7 (stopping in K1) and ID > 7 (stopping K2 - K8). For ID = 7, the energy loss is determined in D6, a 500 μ thick detector. For ID > 7 the energy loss is determined in a 5 mm detector which has superior intrinsic resolution. The "resolution" is determined by the tail of the ^{4}He in between the distinct ^{3,4}He tracks. In the right hand plot, the radius cut has been reduced to $R < 18.75$ mm. A careful comparison of the two plots shows improved "resolution" by retaining only events farther away from the edges of the detectors. Combining this type of cut with stringent requirements on the consistency of the signals in all of the detectors in the stack and the angle of incidence provides the best overall resolution for the helium isotopes.

The results of this improved analysis procedure are shown in Figure 5 for the GCR helium. Note that there is little or no overlap between the abundant ^{4}He and the ^{3}He, particularly for ID > 7 events. In either case, there is no problem in separating the helium isotopes.

Applying this procedure to the SEP events results in the histograms shown in Figure 6 a-c for each of the twelve flares that have been analyzed. The insets give an expanded view of the ^{3}He region of the mass histogram. Analyzing each of these plots allows the ^{3}He/^{4}He ratio to be determined or an upper limit on the ratio to be set. Clearly, for very small flares (low fluence) and small ^{3}He/^{4}He ratios, the instrument may not observe sufficient events to determine an accurate ratio. This is shown in Figure 7 along with the values that have been determined. The cross-hatched region is our estimate of the "space" unavailable to the ONR-604 instrument. The vertical axis gives the amplitude or fluence, i.e. the helium spectrum integrated over the duration of the flare. The three flares for which we determine only upper limits to the ratio are shown as circles. (Note that the solar coronal value for ^{3}He/^{4}He is 0.04%.)

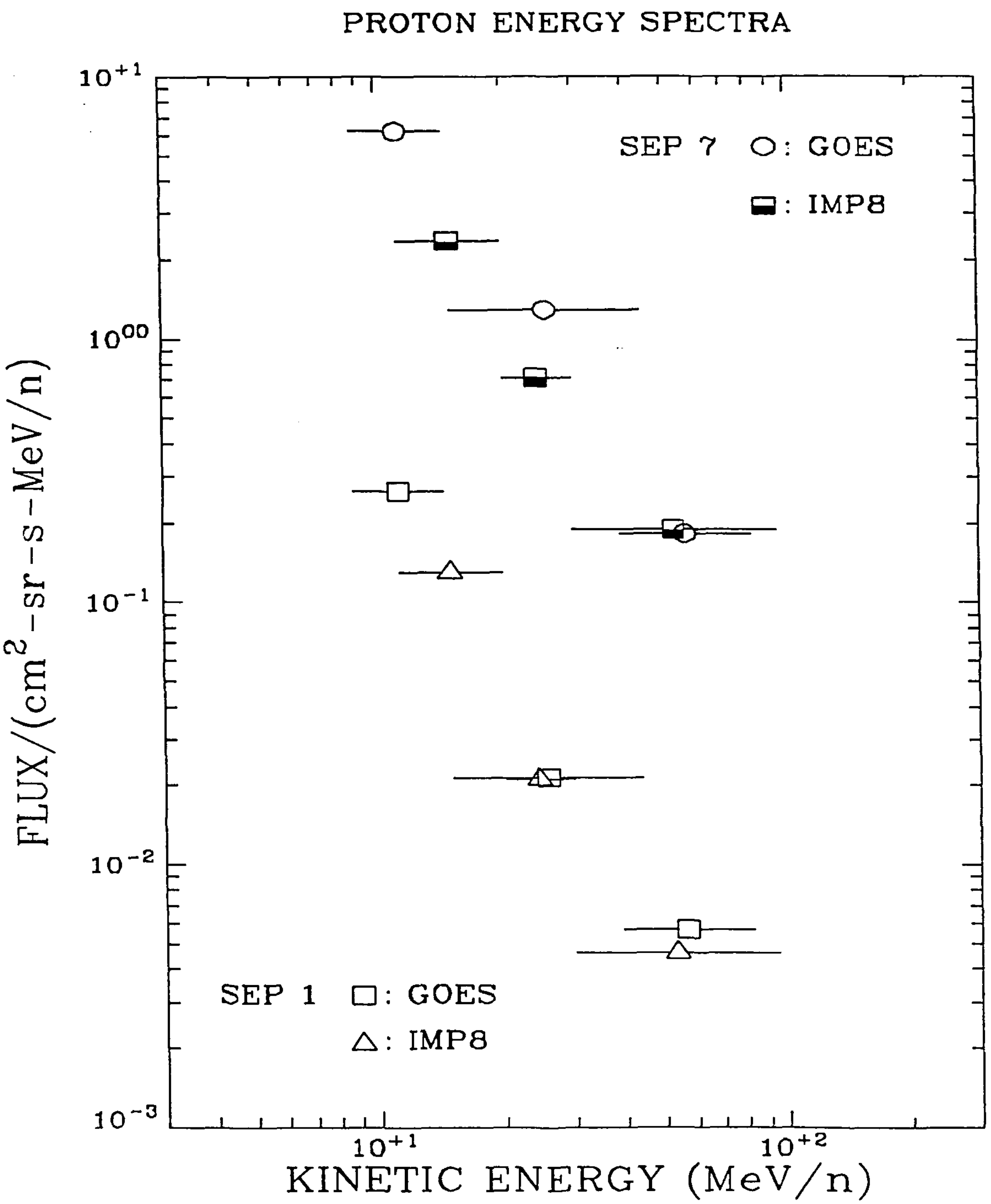


Figure 3. Proton energy spectra for two of the solar flare events determined from GOES and IMP-8 data.

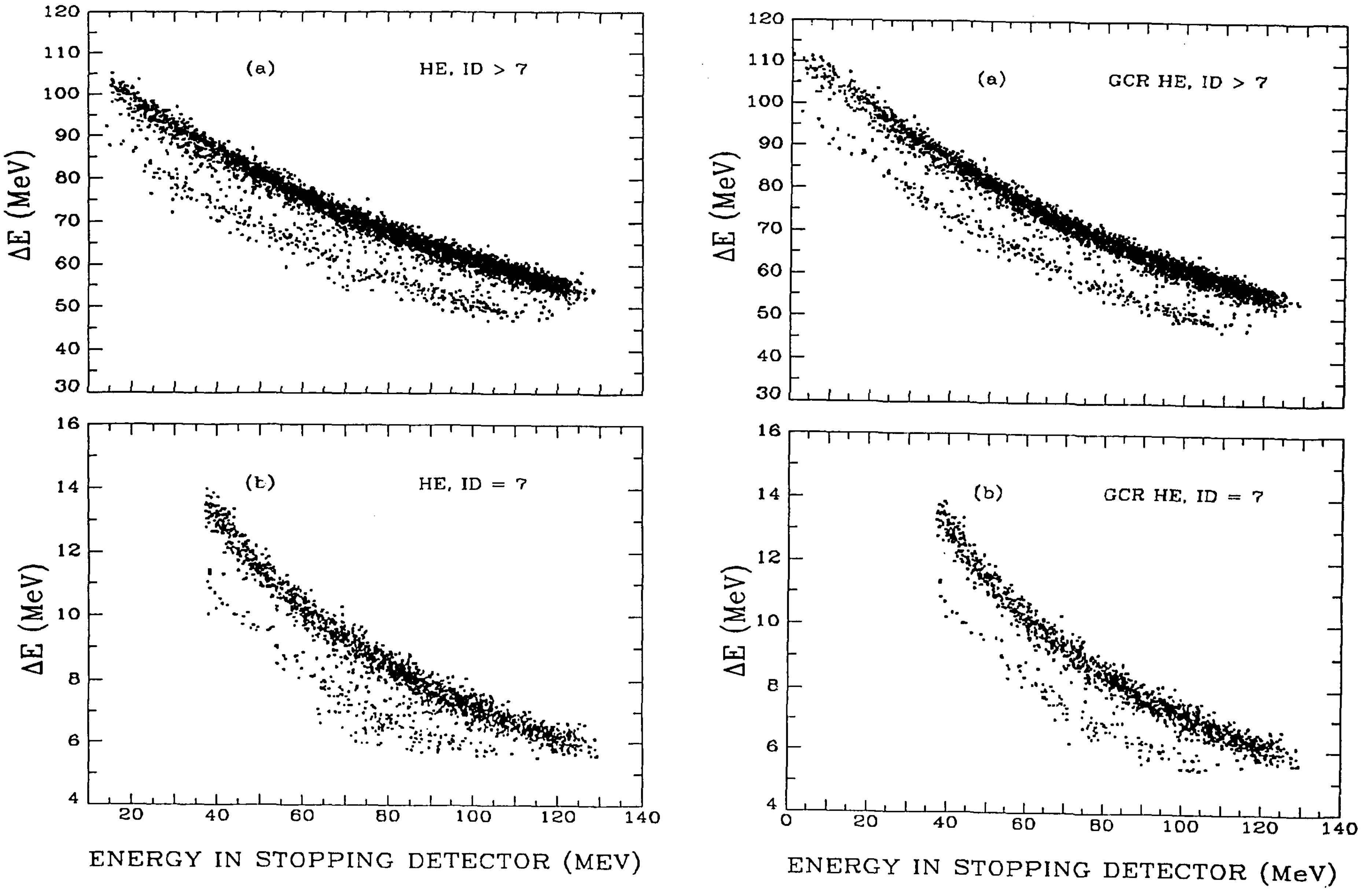


Figure 4. ΔE-E plots for GCR helium nuclei with R<20 mm (left) and R<18.5 mm (right).

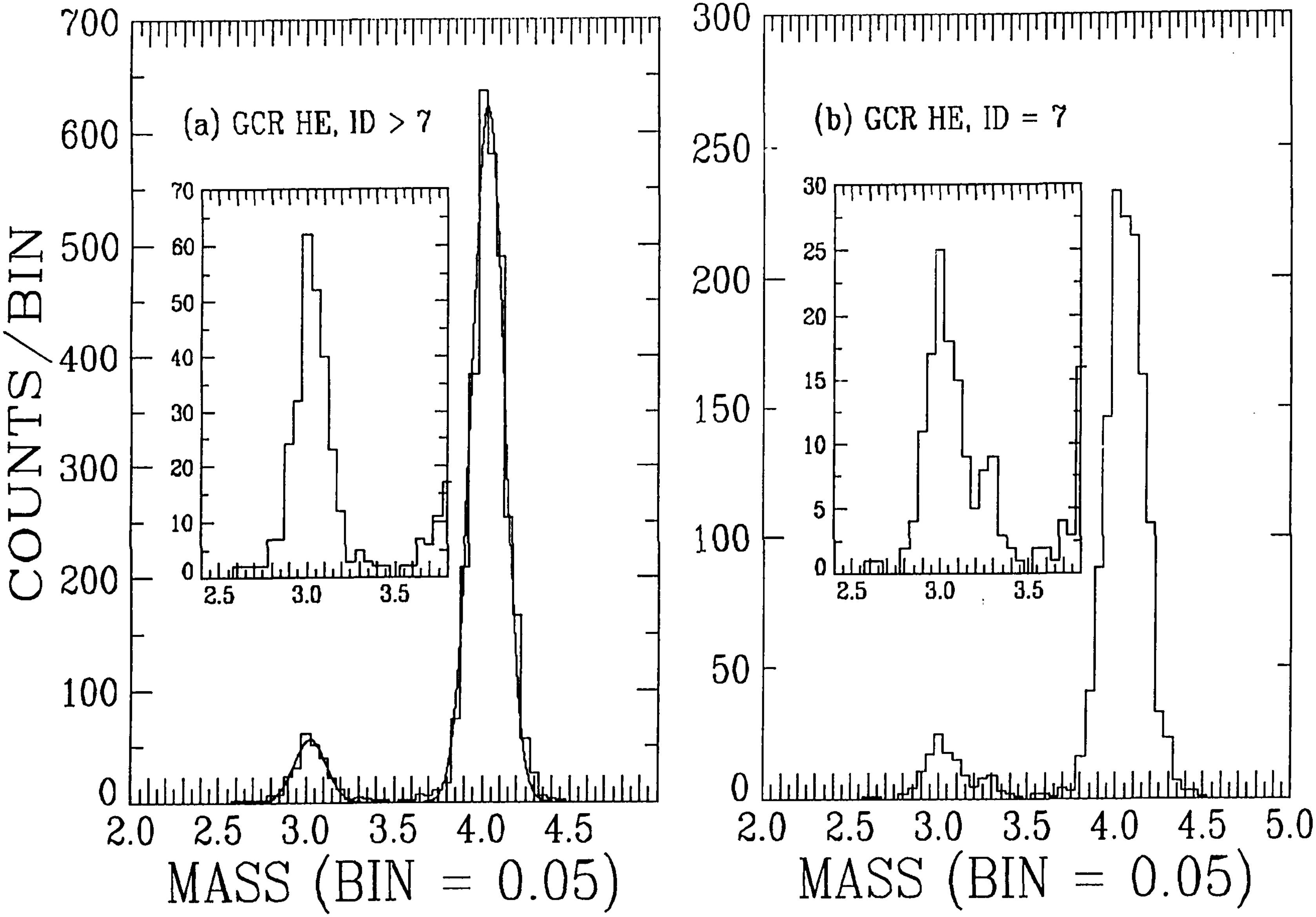


Figure 5. Mass histograms for GCR helium, after all cuts are made, for ID > 7 (left) and ID = 7 (right).

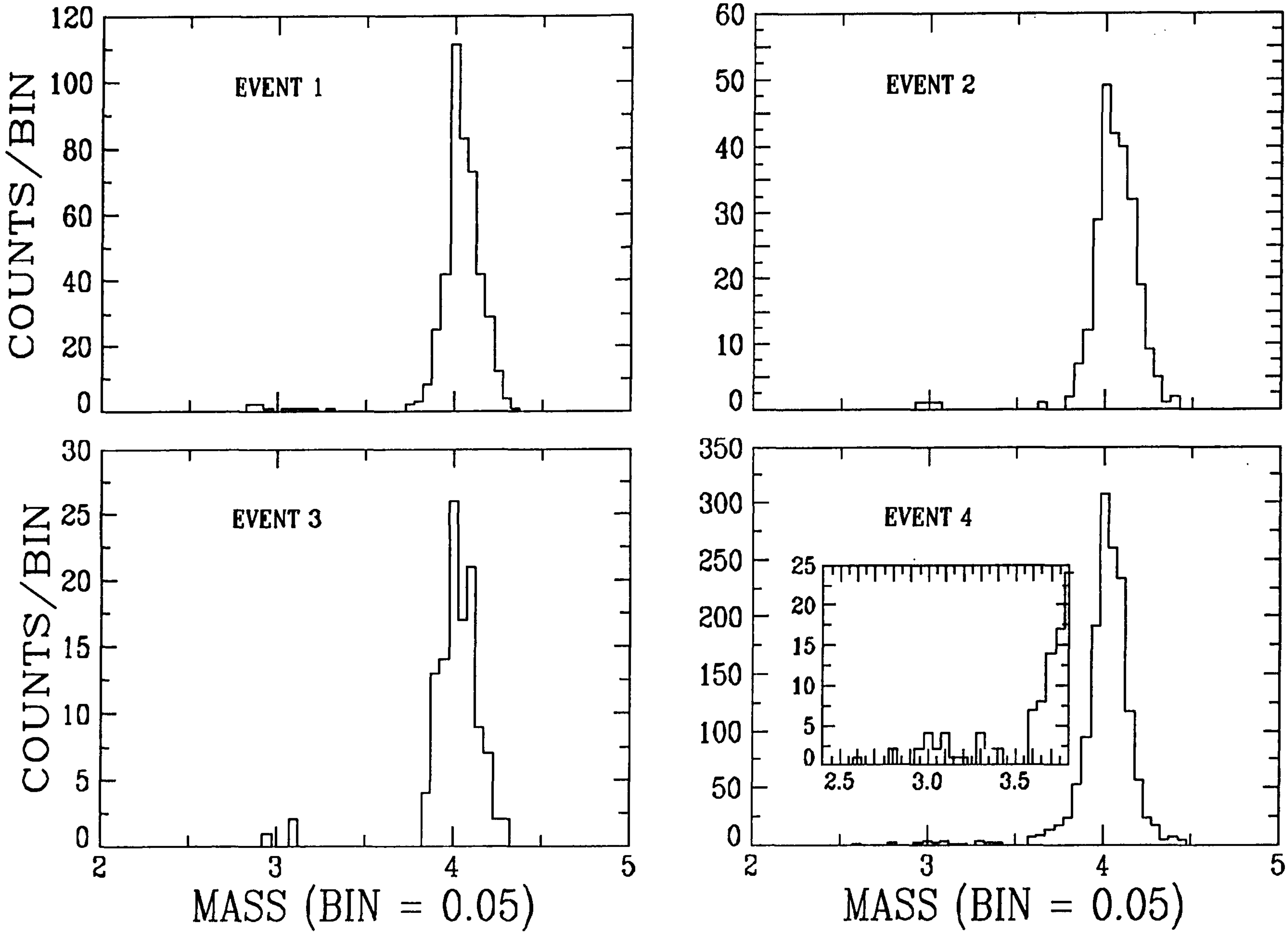


Figure 6a

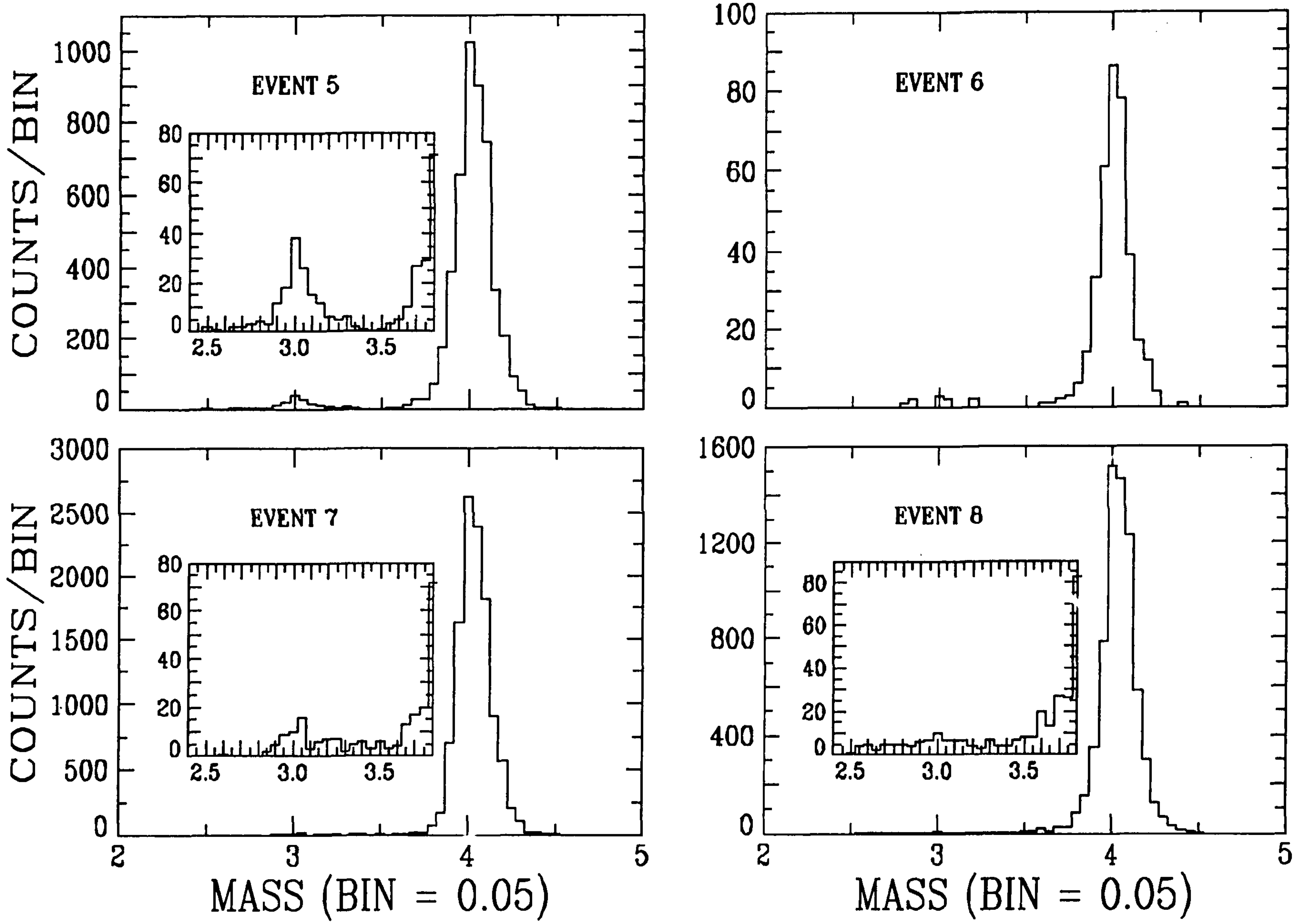
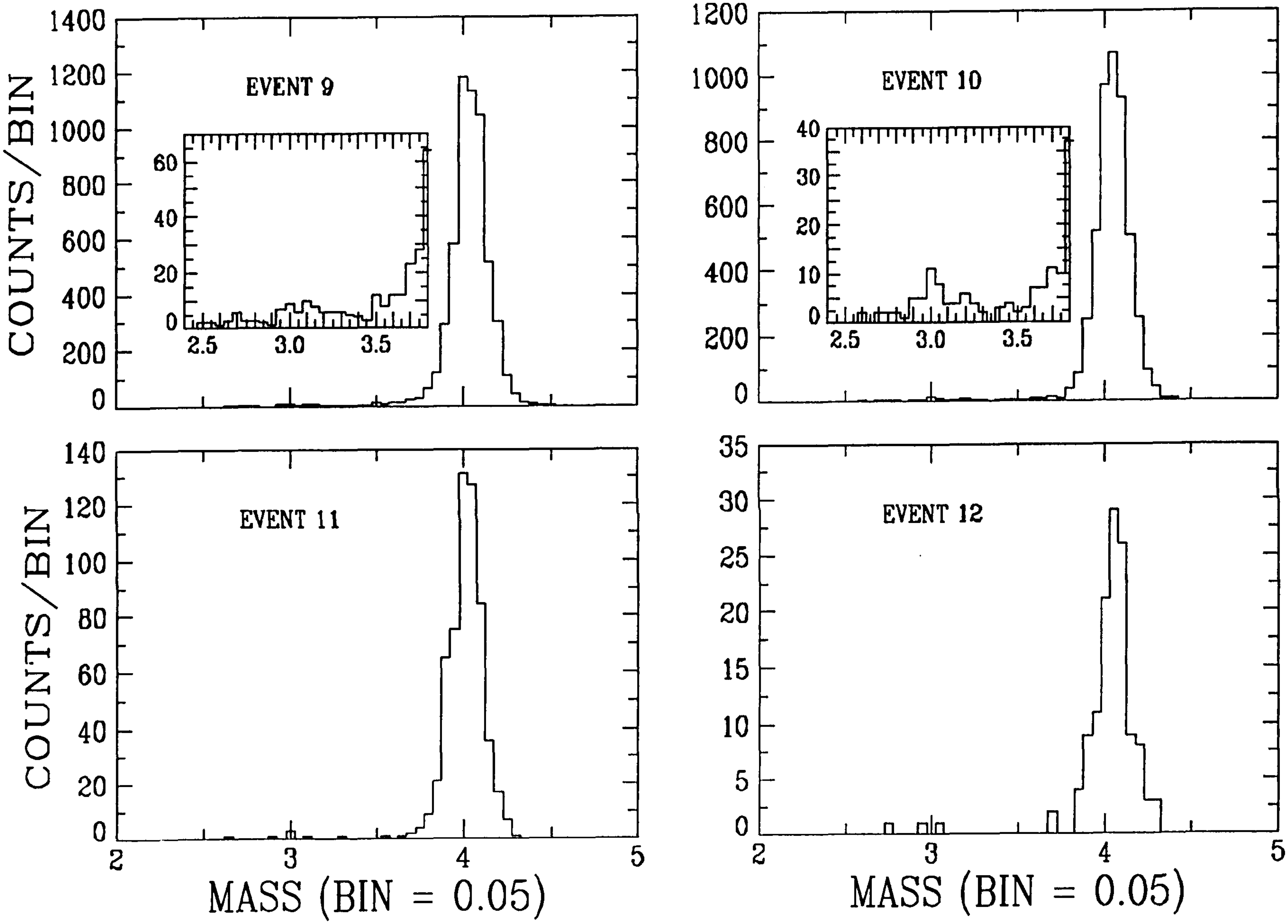

EVENT 5
EVENT 6
EVENT 7
EVENT 8
COUNTS/BIN
COUNTS/BIN
MASS (BIN = 0.05)
MASS (BIN = 0.05)

Figure 6b



COUNTS/BIN
EVENT 9
EVENT 10
EVENT 11
EVENT 12
MASS (BIN = 0.05)
MASS (BIN = 0.05)

Figure 6c

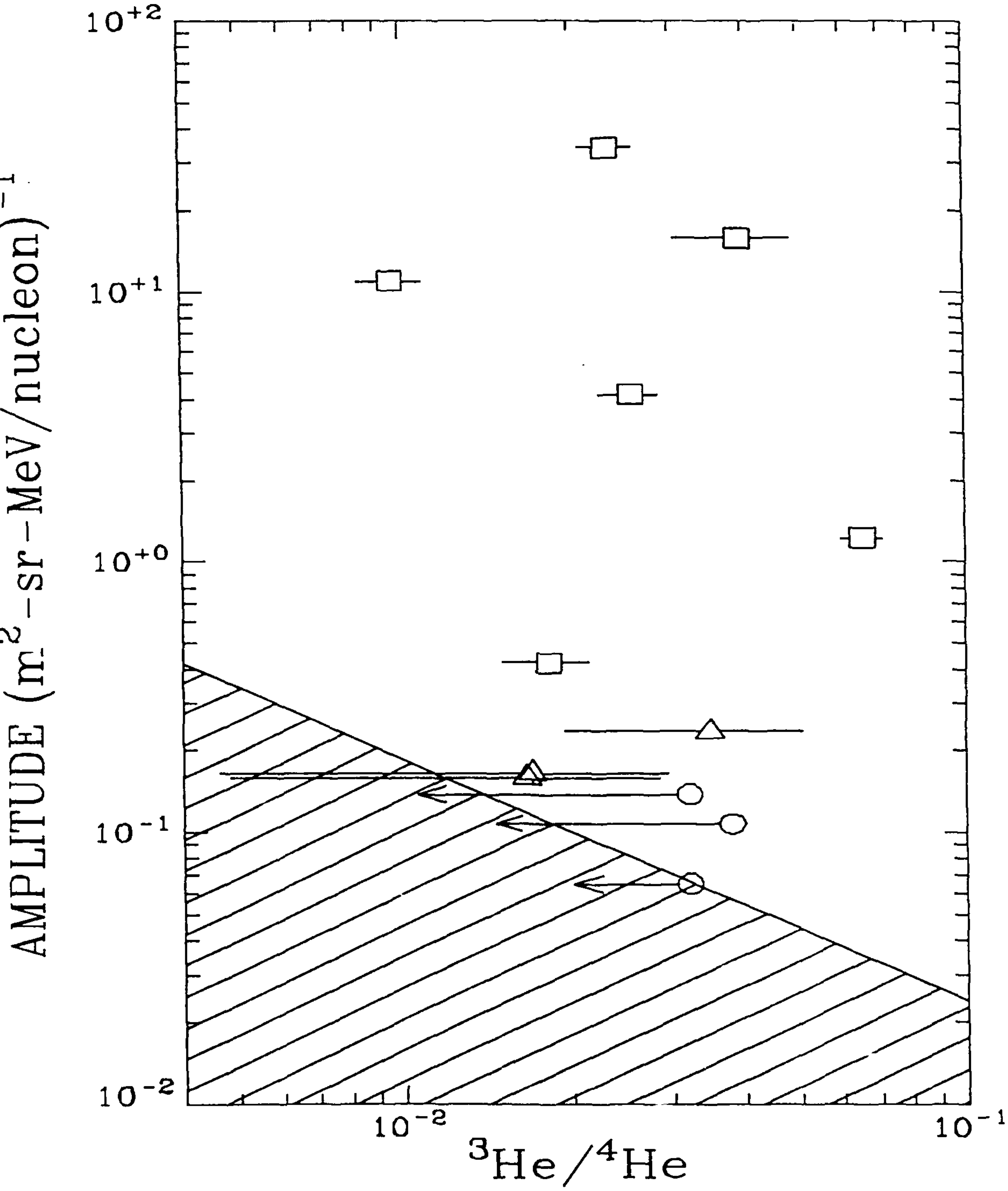


Figure 7. ^{3}He/^{4}He ratios determined for twelve flares during the CRRES Mission. The crossed area indicates the region of amplitude-ratio space in which the ONR-604 instrument cannot determine the ratio.

The largest $^3He/^4He$ ratio (6.5%) is measured for event #5 (24 March 1991) which was only a moderate sized flare in amplitude. The largest amplitude flare, event #8 (11 June 1991) has a $^3He/^4He$ ratio of $2.3 \pm 0.3\%$. The large event of 7 June 1991 (SEP event #7) shows a ratio of ~1%. Previously, we showed that event #5 was heavy ion enhanced while event #7 was heavy ion normal. This correlates with the increased $^3He/^4He$ ratio for event #5. This is one of the only measurements to show such a correlation for the isotopes at high energy.

III. Solar Modulation Level

CRRES was launched near the maximum of the solar cycle when the modulation was high and, consequently, the GCR flux was depressed. Determining the exact level of modulation during the mission is important for heliospheric and environment studies.

Previously, the modulation level has been determined by fitting observed spectra of protons, helium and, sometimes, electrons. The helium has proven to be most useful and we can capitalize on the previous work.

During the last quarter, we adopted an approach based upon the low energy helium flux obtained from the IMP-8 spacecraft. We obtained the "standard" data product, the 25 - 93 MeV/nucleon Helium flux for 1974 - 1991. This low energy Helium is very sensitive to the exact level of solar modulation. Starting with our Local Interstellar Space (LIS) helium spectrum, modulation calculations were performed as a function of ϕ, the modulation parameter. The results were compared to the 25 - 93 MeV/nucleon helium data, and the ϕ value that reproduced the measurements was selected. In addition, the uncertainty in the helium data points was translated into an uncertainty in the corresponding ϕ values. However, there is a potential problem here. The energy range 25 - 93 MeV/nucleon is quite broad and may be subject to the influence of the anomalous helium component, at least during times of solar minimum. Previous analyses have used a restricted energy range, 70 - 95 MeV/nucleon, which should be free from this problem. Unfortunately, the 70 - 95 MeV/nucleon Helium is not a "standard" IMP-8 data product, and we have had to request that it be produced for the full time period through the CRRES mission.

The University of Chicago supplied the 70 - 95 MeV/nucleon data which is shown as daily averages in Figure 8. Next the flare spikes are removed by using the quiet-time cuts, and the data are re-binned into weekly or monthly averages. Repeating the analysis described above will bring our results into accord with other analyses in the literature (allowing direct comparison) and will cross-check the previous results for the modulation parameter.

This analysis has now been completed. Figure 9 shows the results. The top panel shows the 70 - 90 MeV/nucleon helium flux after applying quiet-time selections and binning as monthly averages. Next the modulation calculation for helium is performed as a function of the modulation parameter, ϕ. The spectrum is integrated between 70 and 95 MeV/nucleon producing a flux versus ϕ calibration curve. This is then applied to the data to derive the ϕ vs time plot shown at the bottom of Figure 9. The uncertainties reflect the errors in the measurement of the 70 - 95 MeV/nucleon helium and are representative of the level of uncertainty that exists for a monthly average. Comparison of this plot with the one derived from the 25 - 93 MeV/nucleon helium shows good correlation, except for the solar minimum periods during which the anomalous component is present.

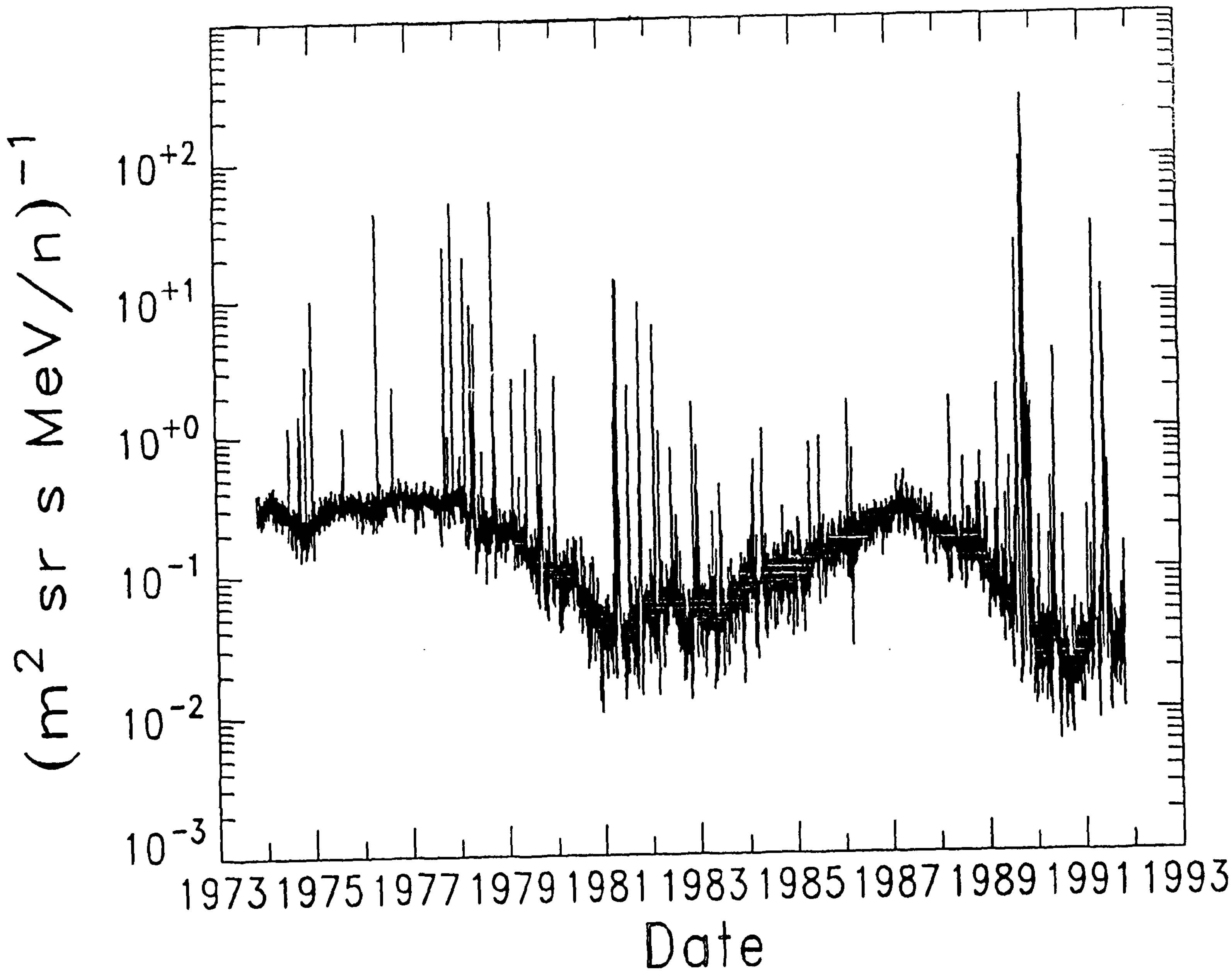


Figure 8. Uncorrected, daily average, 70 -95 MeV/nucleon Helium flux from IMP-8, courtesy of The University of Chicago.

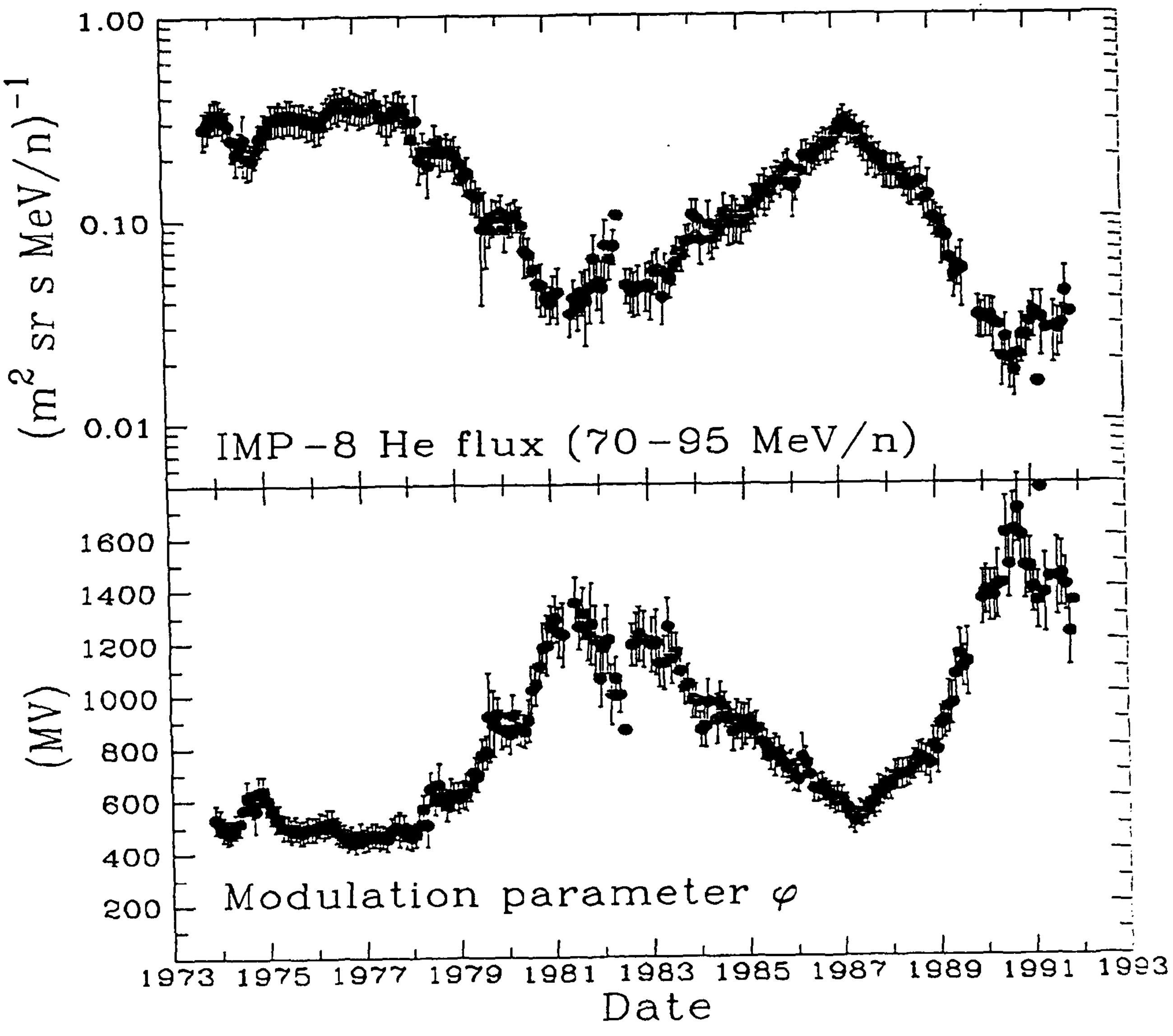


Figure 9. The IMP-8, monthly averaged, 70-95 MeV/nucleon helium flux for 1974-1992 (top) compared to the derived modulation parameter, ϕ, for the same time period.

Note that during 1990-91, the time of the CRRES mission, the modulation reached the highest levels (largest ϕ) that have been observed for the past 20 years, thereby depressing the GCR flux to its lowest level in over 20 years. A tentative value for the average modulation level over the 14 month CRRES mission is $\phi = 1480$ MV. From the literature, the solar maximum in 1969 was characterized by a level of $\phi \sim 1100$ MV, considerably less than in 1991.

We have attempted to validate the results of Figure 9 by comparing the derived modulation parameter, ϕ, to results in the literature. Our first summary of literature values is plotted over the calculated results in Figure 10, and the overall agreement (up to 1981) is good, within the average uncertainties shown in Figure 9.

However, a close inspection of Figure 10 shows that our derived modulation level is still 6 - 8 % above most of the literature points. This may be a systematic effect that requires further investigation. We suspect that the strong presence of the anomalous helium during the 1974 - 79 solar minimum period may have contributed slightly to the helium flux even in the 70 -95 MeV/nucleon energy region. Since the anomalous helium was not included in our calculations, this is a potential systematic effect that could lead to the observed discrepancy. Therefore, a task for the next period is to include the anomalous helium, explicitly, to look at the possible effects. The anomalous helium local interstellar spectrum must be determined separately so that calculations can be done both with and without this component.

The Helium flux in Figure 9 appears to track the Climax neutron monitor rate quite well. The neutron monitor, of course, tracks solar activity and, thereby, the solar modulation. Thus, by correlating ϕ to the Helium flux, we may be able, also to correlate ϕ to the neutron monitor. Since several solar cycles of neutron monitor results are available, they can be used to extrapolate to future solar cycles, thus providing a means to predict ϕ, and to estimate the GCR flux for future times.

To investigate this possibility we have correlated the ϕ values with the Climax Neutron Monitor counting rate, and the result is shown in Figure 11. While the general trend is what would be expected, the overall correlation is not very good. The same level of ϕ does not always lead to the same neutron monitor rate. This may be the well-known hysteresis between particles of different rigidity, or may signify different processes of modulation for different periods within a solar cycle.

To investigate this behavior further, we divided the full time period into intervals. The two rising parts of the cycle, May 78 - Dec. 80 and April 87 - Aug. 90 should give comparable dependences. These are shown in Figure 12, with the earlier period at the top. Note that the trend in the curves is the same, but the rate of change is much larger for the bottom plot. Also, the range of values covered, in both axes, is larger in the 1987-90 period. This is evidence that the 11 years cycles are not the same, implying that the solar cycle is a 22 year epoch rather than the standard 11-year cycle that is usually assumed. Considerably more work will be required to understand these trends in detail before a good predictive capability can be developed.

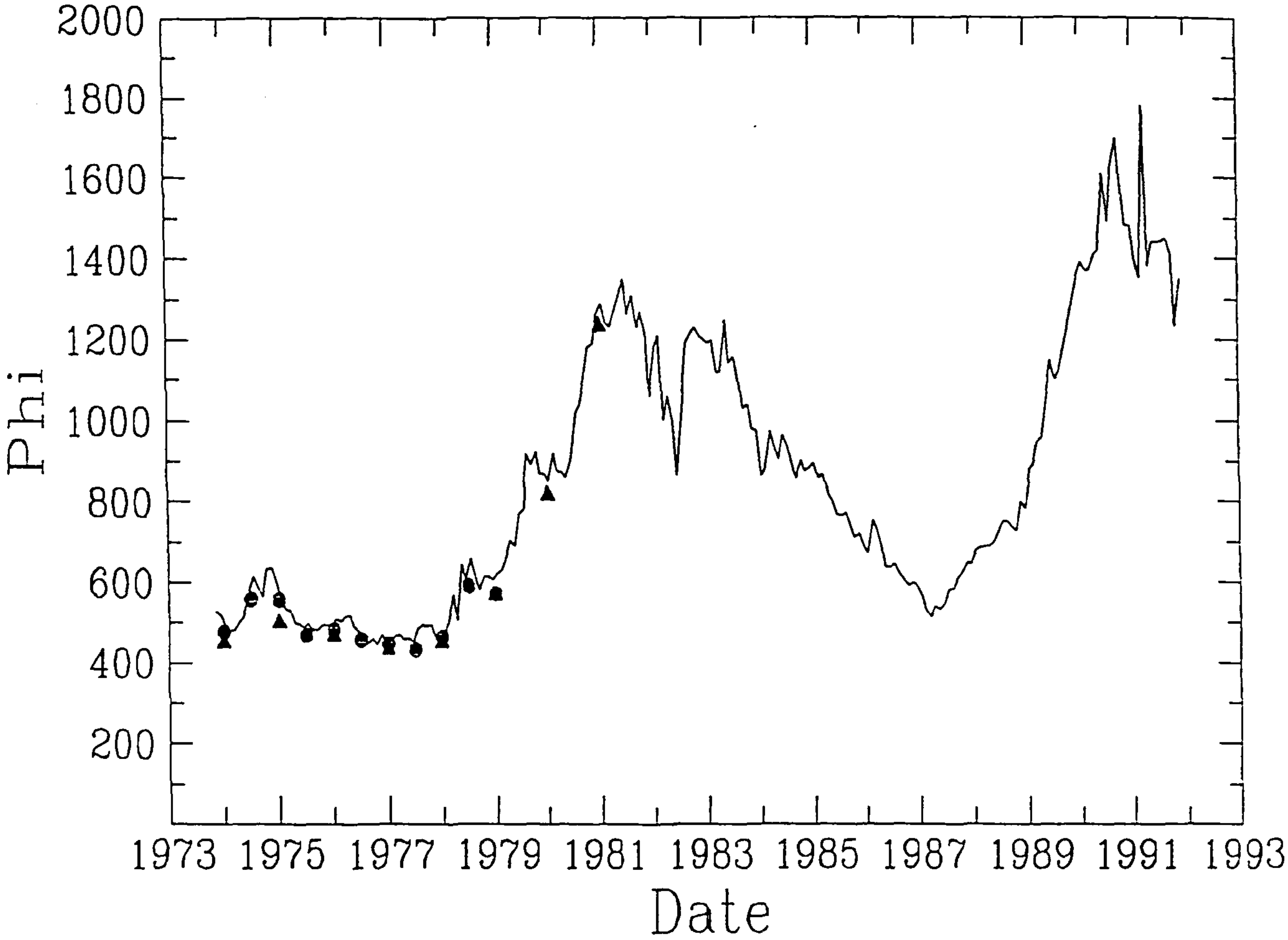


Figure 10. Comparison of the derived values of ϕ to values reported in the literature (circles and triangles).

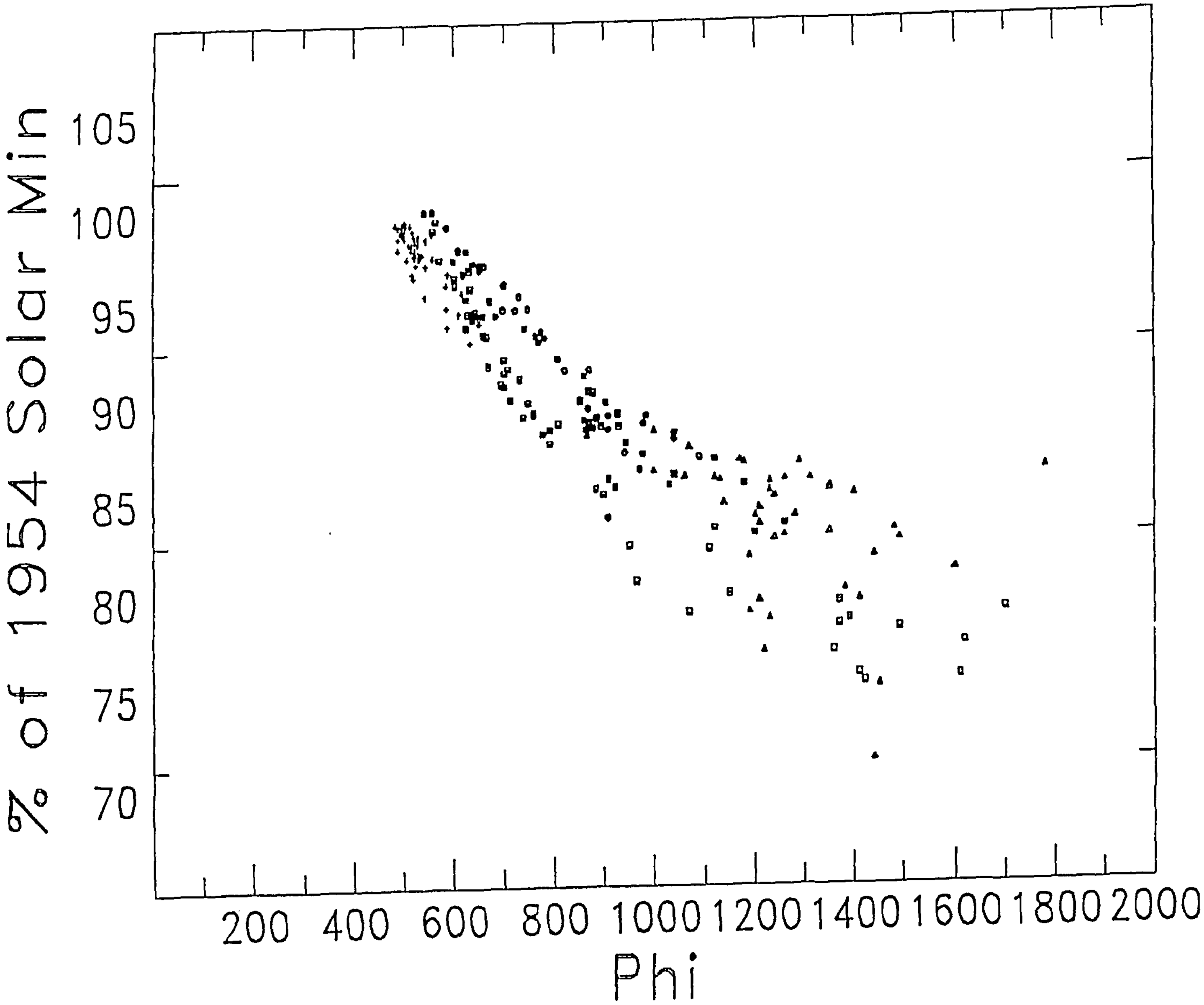
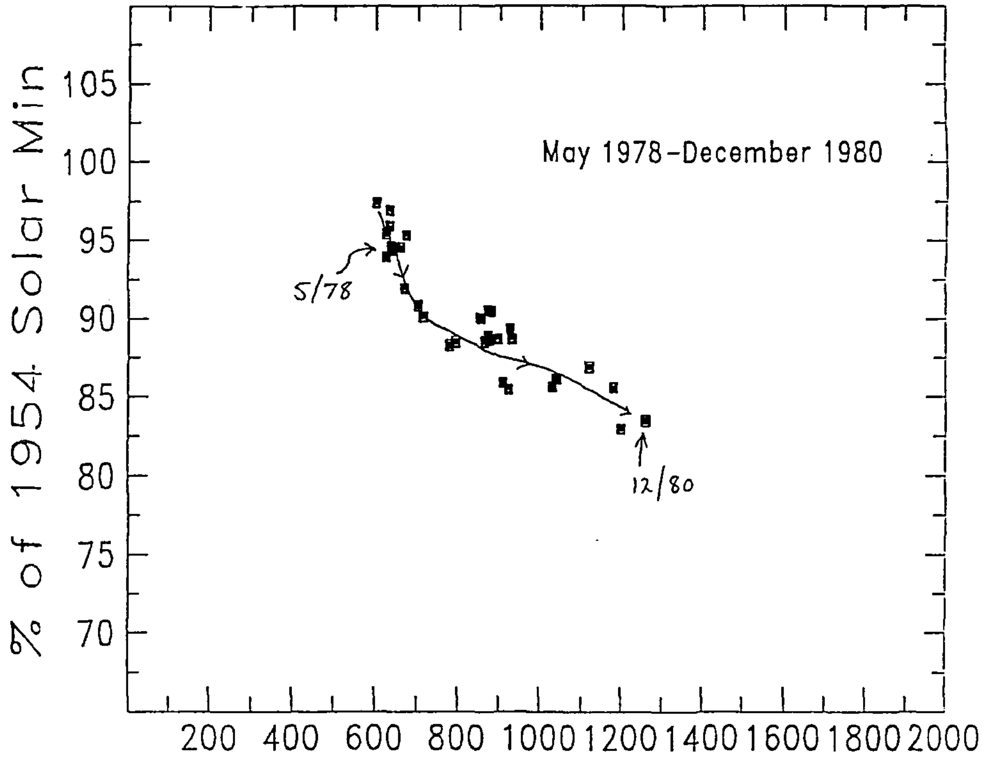


Figure 11. Correlation plot of Climax Neutron Monitor counting rate vesus derived value of ϕ for 1974-1992.



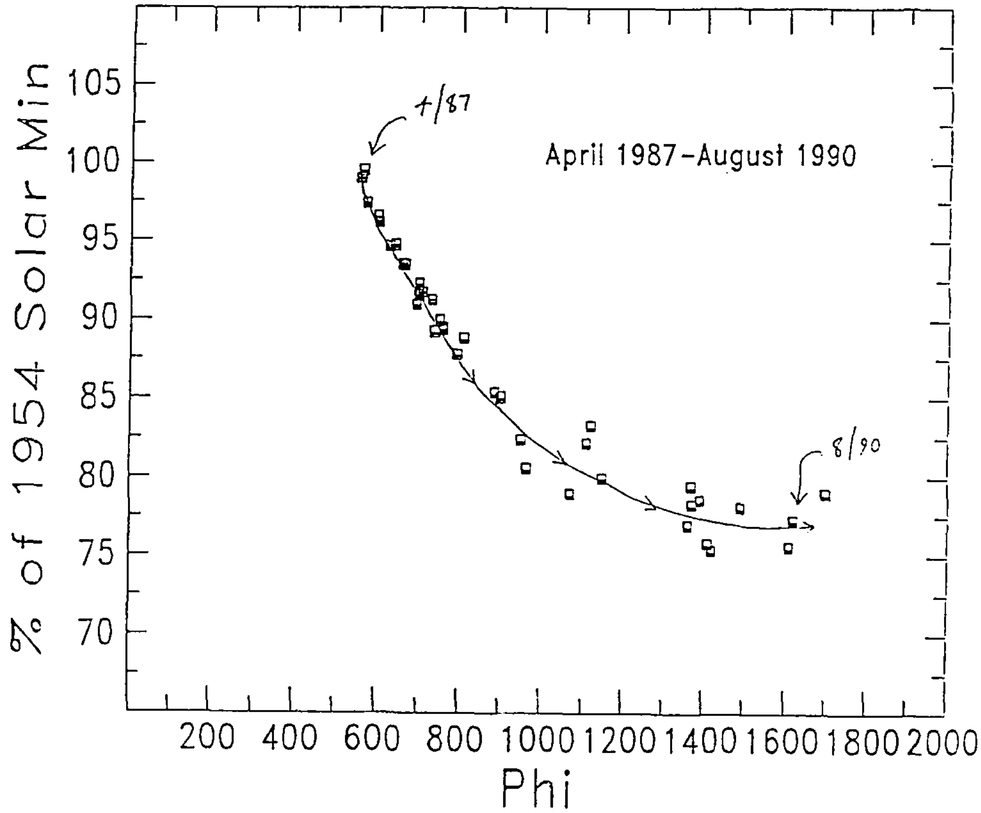


Figure 12. Correlation plots of ϕ vs Climax for the two rising portions of the solar cycle 1978-80 (top) and 1987-90 (bottom).